Latest Cross Section Results from MiniBooNE

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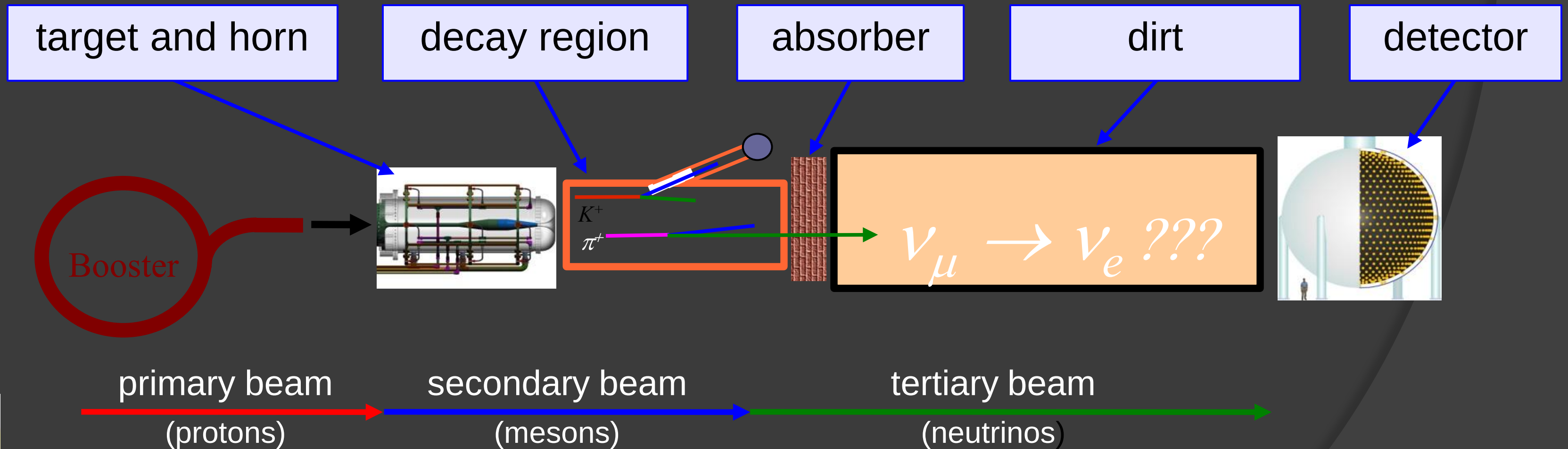
MiniBooNE Experiment – E898 at Fermilab

Test of LSND within the context of $\nu_\mu \to \nu_e$ appearance only is an essential first step:

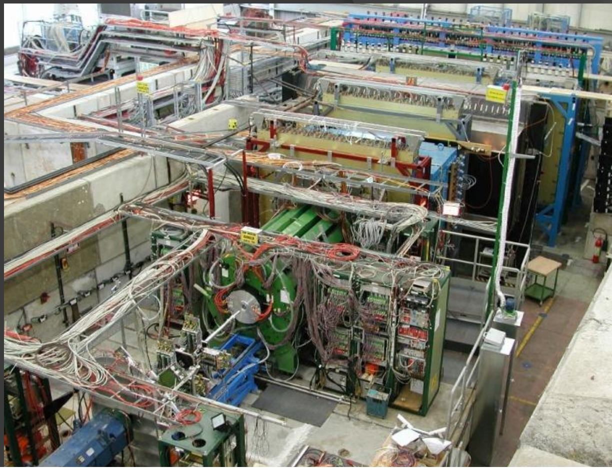
- Keep the same L/E
- Higher energy and longer baseline – E=0.5 – 1 GeV; L=500m
- Different beam
- Different oscillation signature ν_μ–>ν_e
- Different systematics
- Antineutrino-capable beam



Flux - π^+ Production from HARP

HARP (CERN) measured the π^+ production cross section

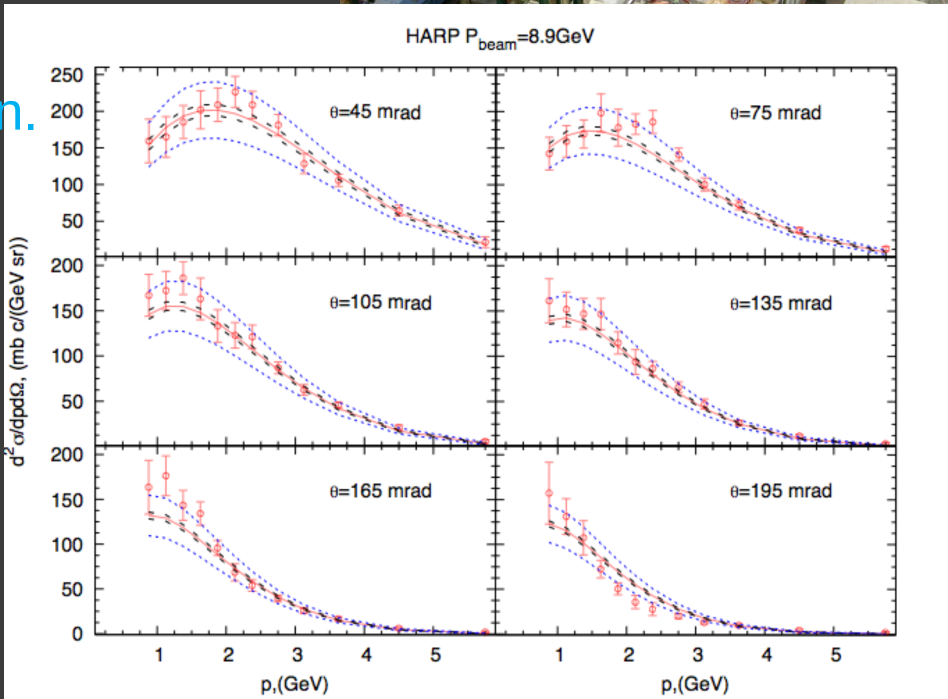
- 5% λ Beryllium target
- 8.9 GeV proton beam momentum



π^+ production cross section is parameterized from a fit to HARP π^+ production cross section, using the standard Sanford-Wang parameterization.

Covers 80% of the pion phase space relevant for MB. Pion production uncertainty is 7%.

Makes cross section measurements possible.



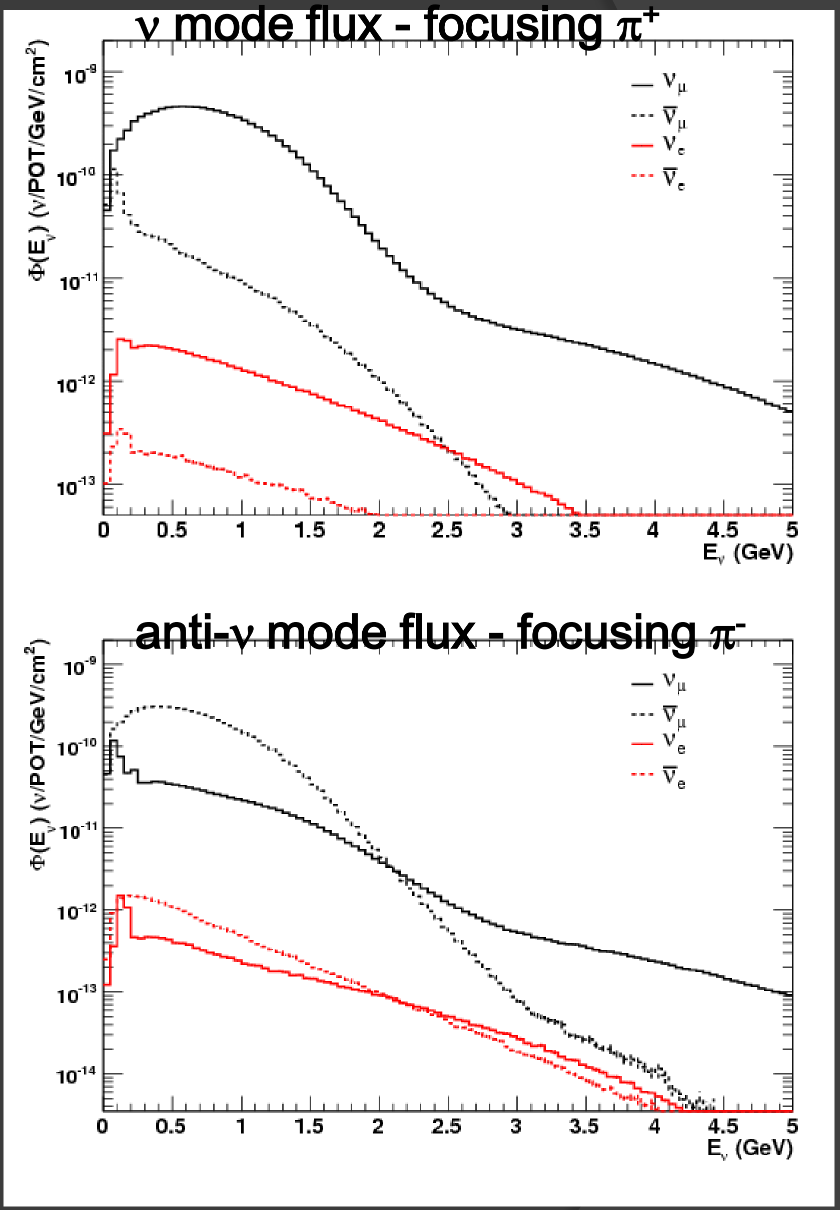
M. Catanesi et al., Eur. Phys. J. C52, 29 (2007)

MiniBooNE Predicted Flux

•~1,000,000 interactions in fiducial volume in ν mode with small anti-ν component.

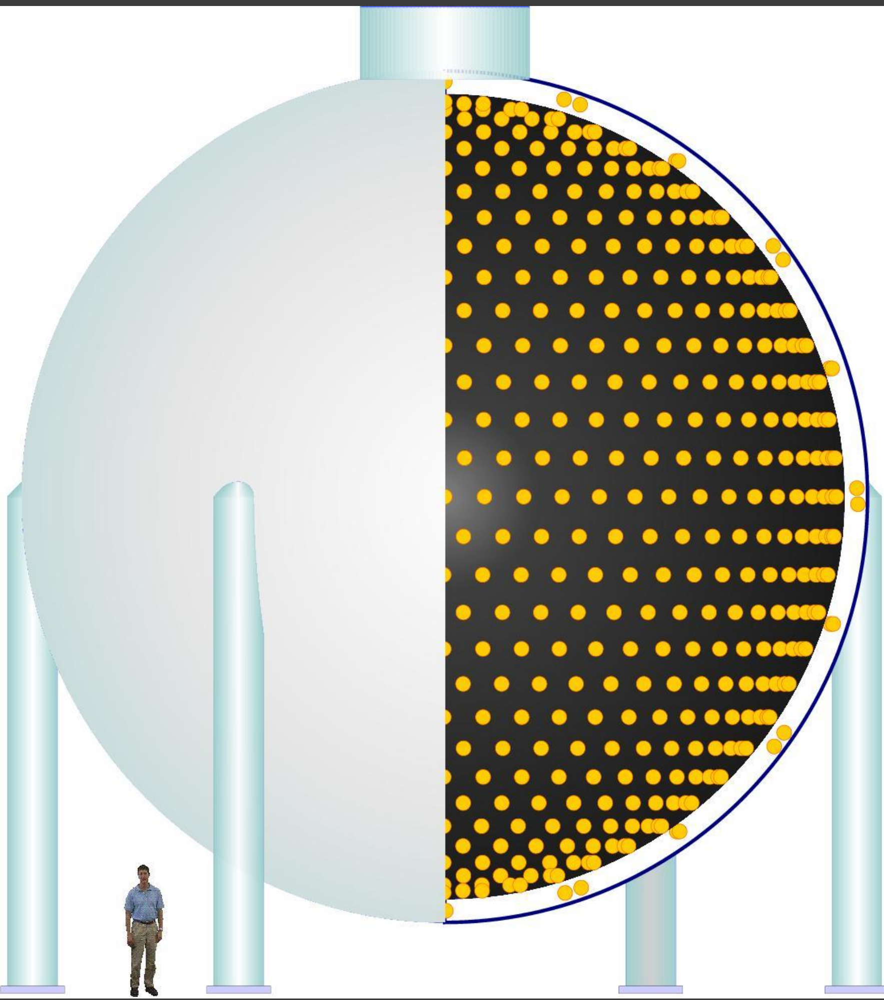
• greater than 100 k interactions in fiducial volume in anti-ν mode with 30% ν component.

Largest sample neutrino and anti-neutrino interactions in the ~1GeV region to date.

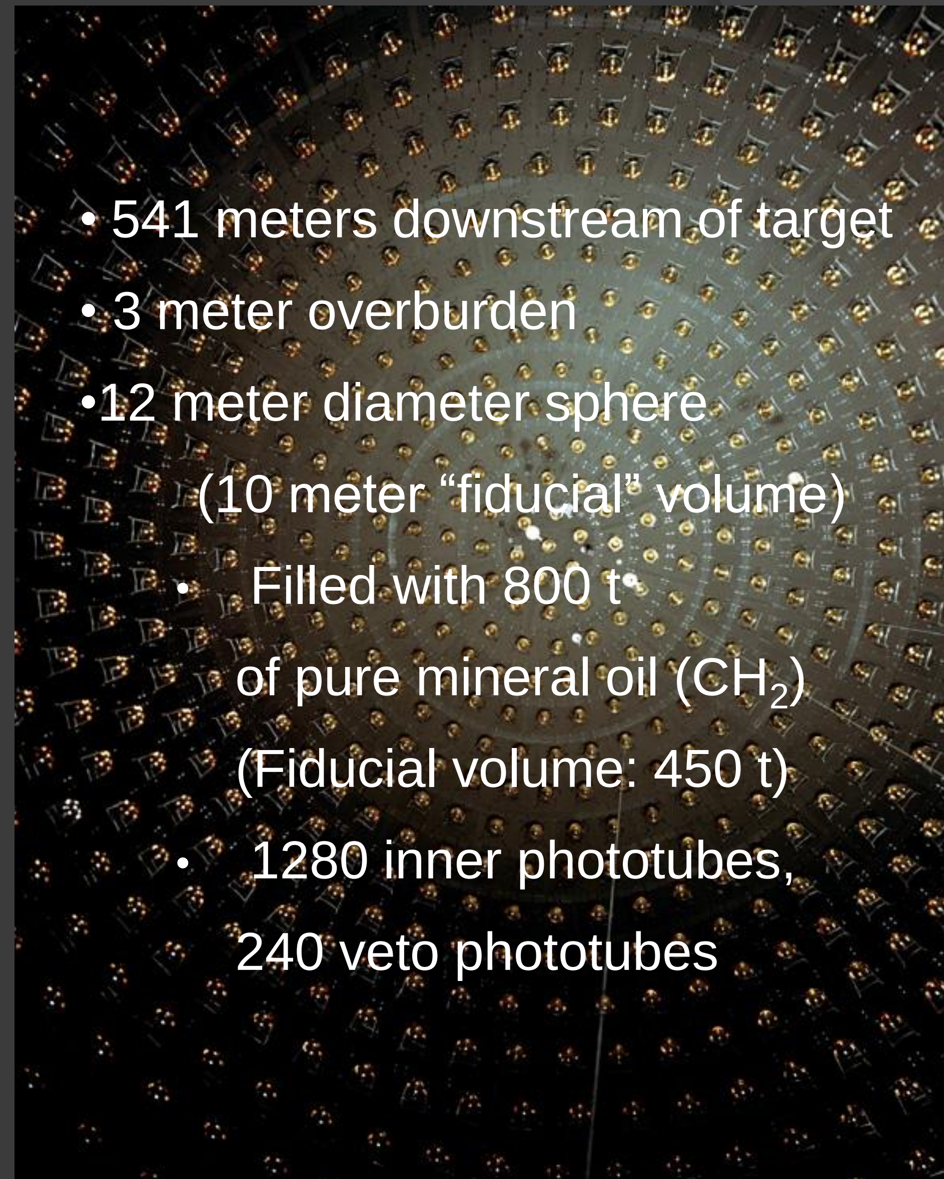


A.A. Aguilar-Arevalo et al., PRD 79, 072002 (2009)

The MiniBooNE Detector



A. A. Aguilar-Arevalo et al., NIM A599, 28 (2009)



- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere

  (10 meter “fiducial” volume)

  - Filled with 800 t of pure mineral oil (CH_2)

    (Fiducial volume: 450 t)

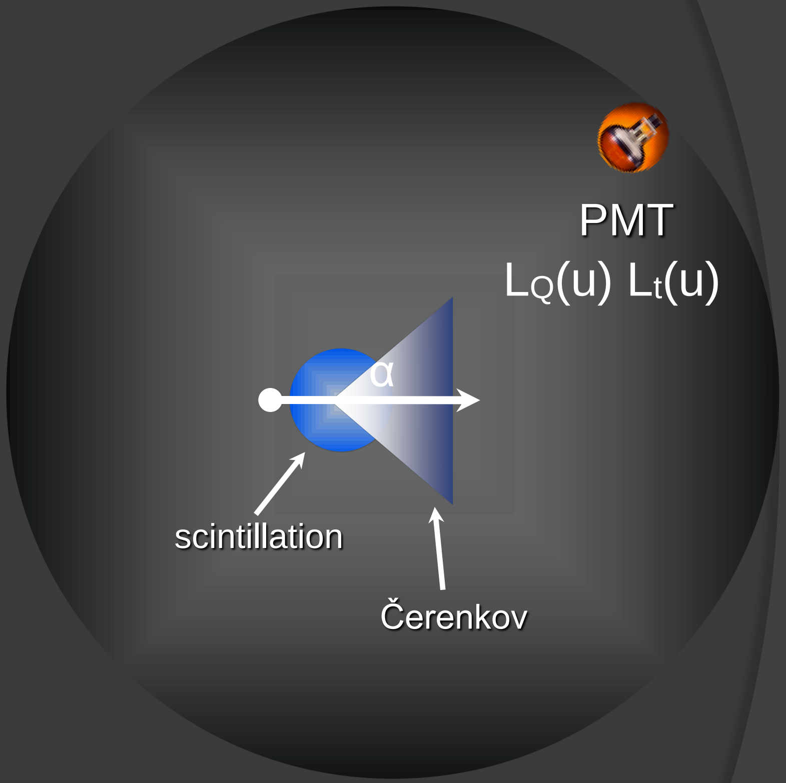
  - 1280 inner phototubes, 240 veto phototubes

Track Fitting

- A particle is parametrized as a “track” in the oil.
  - Vertex: (x,y,z)
  - Time: (t)
  - Direction: (θ,φ)
  - Kinetic energy: (E)

- At each point of the track scintillation and Čerenkov light is produced. This depends on the type of particle.

- This light propagates through the mineral oil to the PMTs.



R.B. Patterson et al., Nucl. Instrum. Meth. A608, 206 (2009)

Neutrino Cross Sections Extraction Technique

$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \Phi_i N_{targs}}$$

σ – cross section,

E_ν – neutrino energy,

U_{ij} – unfolding matrix,

N_j – measured rate in bins,

B_j – measured/predicted background rate in bins,

Φ_i – flux,

ε – efficiency.

Unfolding

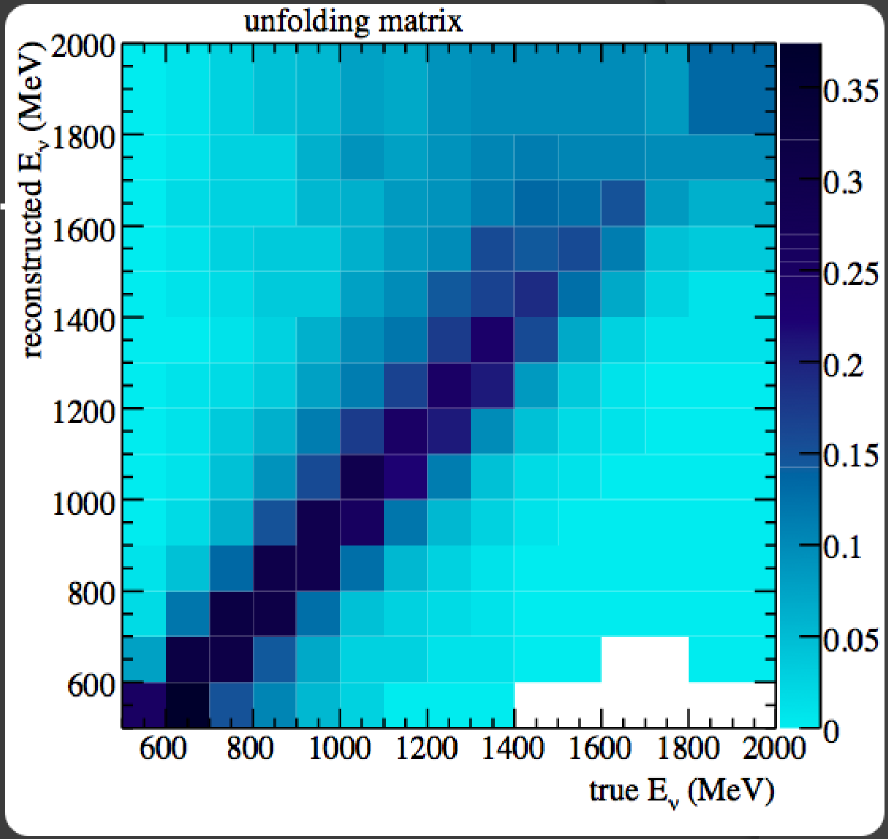
Unfolding is used to correct for detector effects (smearing and mis-reconstruction).

- bin migration matrix inversion is unbiased, but it's unstable and leads to large statistical uncertainty.

Bayesian unfolding:

$$U_{ij} = P(t_i | r_j) = \frac{P(r_j | t_i) P(t_i)}{\Sigma P(r_j | t_n) P(t_n)}$$

- small statistical uncertainty,
- small bias is the price.

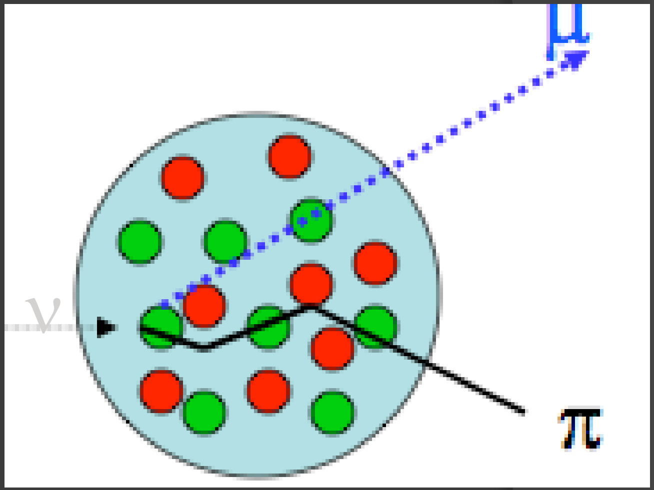


CCπ^0 unfolding matrix.

Observable Cross Sections

$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \, \Phi_i \, N_{targs}}$$

- nuclear target – re-interactions in the nucleus.



- different primary neutrino interactions become indistinguishable experimentally.

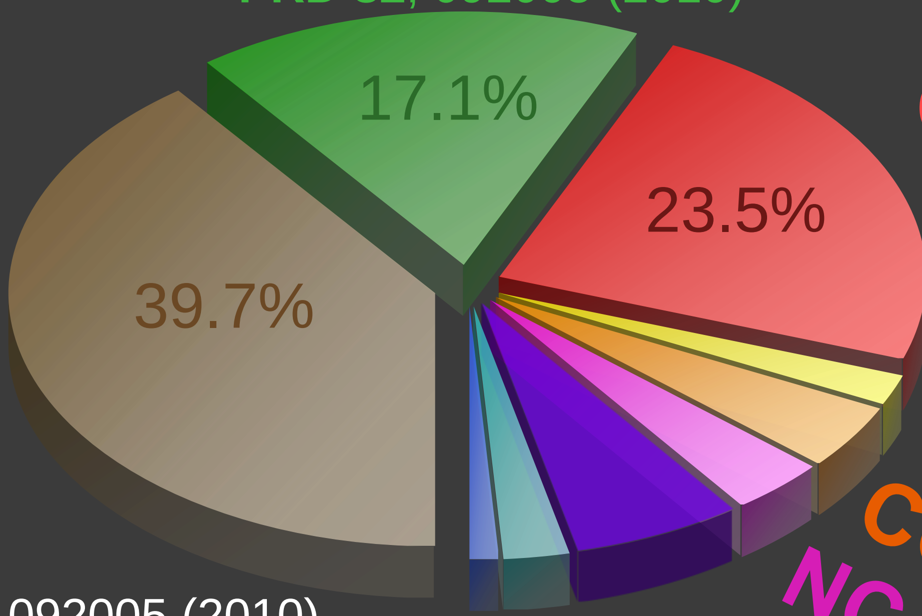
- Final State Interactions (FSI) model is needed to extract nucleon cross section – large uncertainties.

- MiniBooNE measures observable cross sections. $CC\pi^+$ observable signal include all events with a μ^- and a π^+ emerging from the nucleus.

MiniBooNE ν Cross Section Measurements

NC EL

PRD 82, 092005 (2010)



CC π^+

PRL 103, 081801 (2009)
PRD 83, 052007 (2011)

multi-π^+

CC π^0

PRD 83, 052009 (2011)

NC $\pi^{+/-}$

NC π^0

PRD 81, 013005 (2010)
PL B664, 41 (2008)

QE

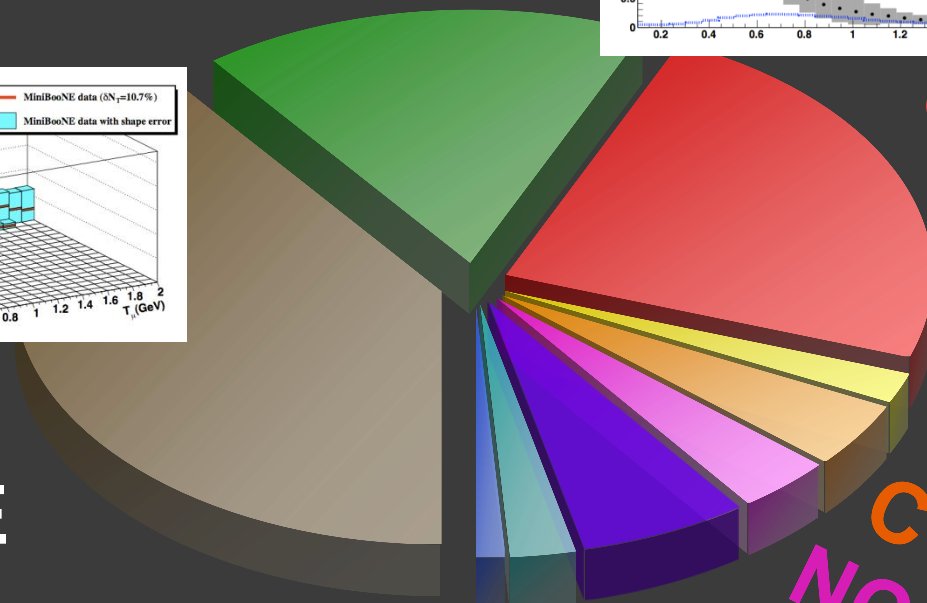
PRD 81, 092005 (2010)
PRL 100, 032301 (2008)

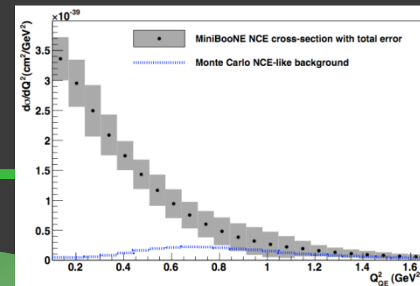
WS other

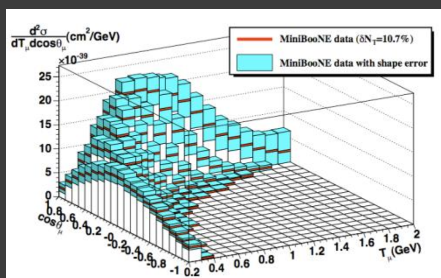
NUANCE

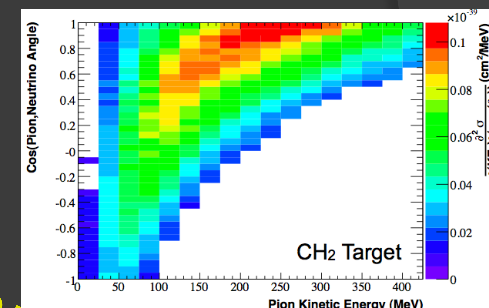
MiniBooNE ν Cross Section Measurements

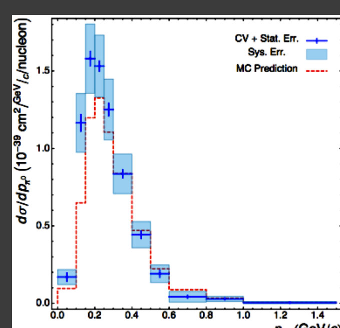
Collected ν data
2002-2005, 2007
6.46e20 POT

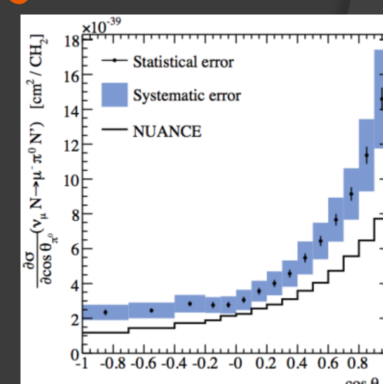






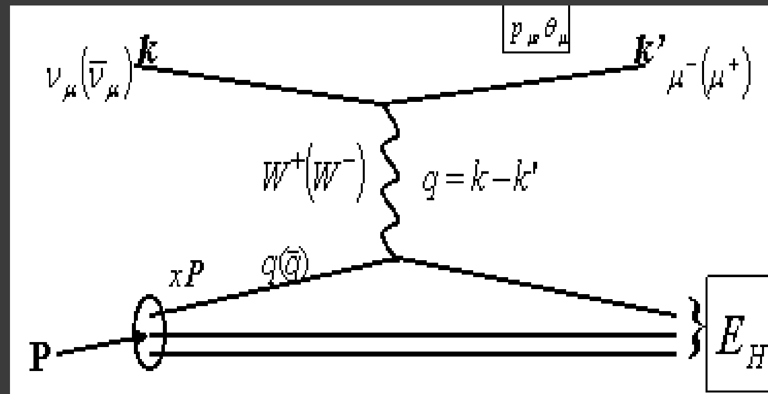






1st time full kinematics have been reported for many of these reaction channels!

MiniBooNE CC Inclusive Cross Section



Can't we just add CCQE, CCπ^+ and CCπ^0?

- Yes, we can add the cross sections, but we'll be adding the systematics as well.

- Complicated model dependent correlations – each of the exclusive channels is a background for the others through FSI model.

It's important to have a full suite of cross section measurements from one experiment – same flux systematics.

CC Inclusive Sample in MiniBooNE

Selection criteria:

- Events are tagged by at least one Michel electron,

- Veto and Containment – Maximum of five VETO hits in all subevents,

- Minimum PMT hits in the first subevent to remove beam unrelated backgrounds.

- Fiducial volume of 5m diameter.

CCQE – 52%
CCpip - 36%
CCpi0 - 5%
Other CC – 3%
NC – 3%

Data events after cuts 344k. 96% purity.

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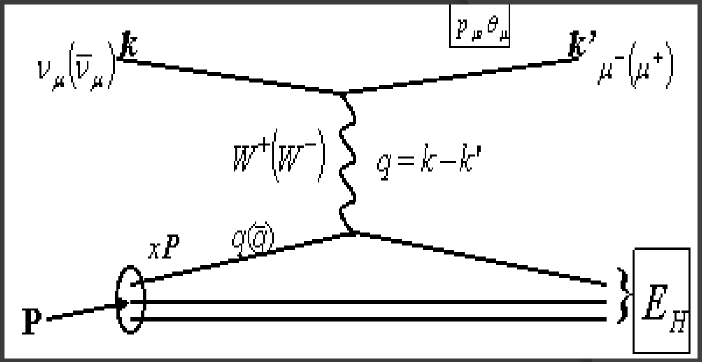
CC Inclusive Event Reconstruction

New event reconstruction for MiniBooNE

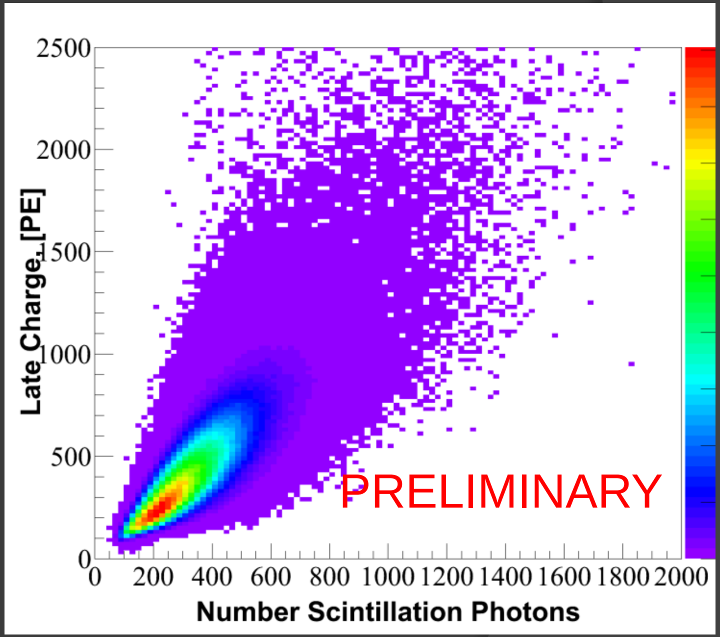


- Muon kinematics from 2-track likelihood fit:

  Second ring of the fit absorbs the bias due to second most prominent ring.

- Neutrino energy – MiniBooNE detector as calorimeter.

  Small scintillation light component produces late hits in the event. The charge of the late hits is used as a measure of the neutrino energy.



Fully reconstruct the lepton vertex – no assumptions for the target!!!

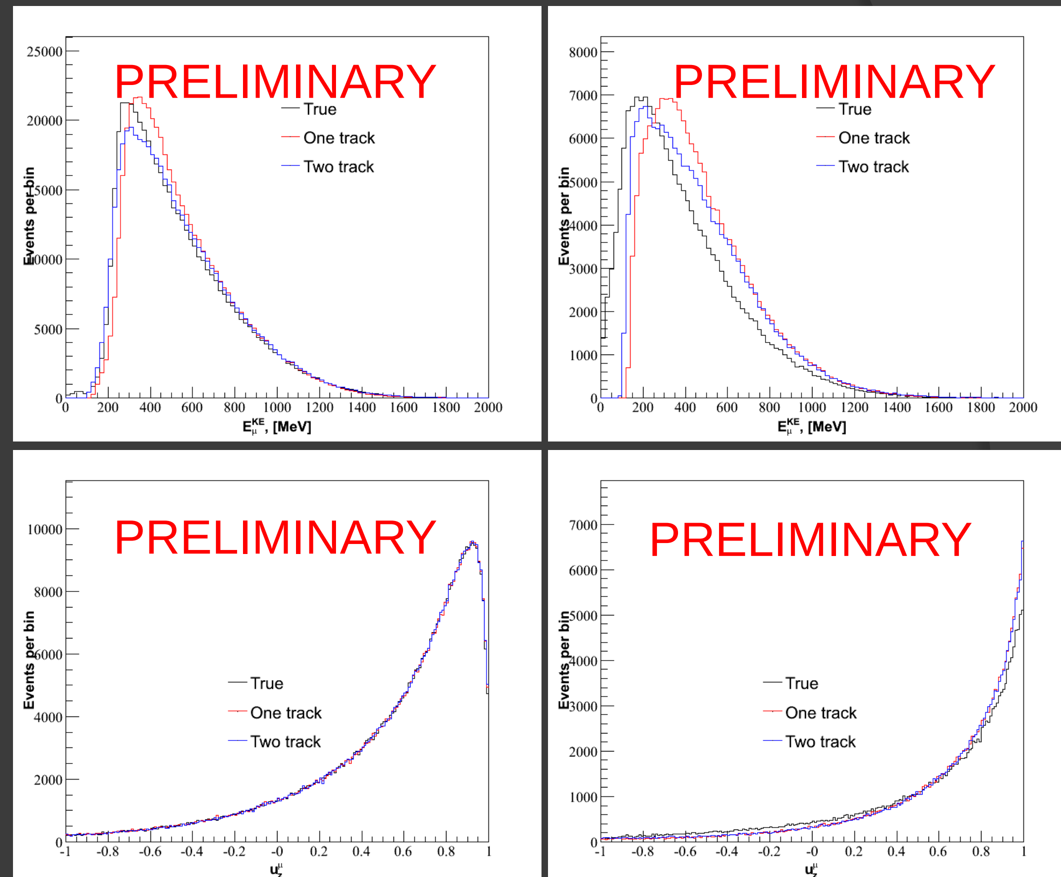
Plots are from MC.

Muon Kinematics Reconstruction Performance

2-track fit improves significantly the reconstruction of the muon kinetic energy compared to one track fit. Muon kinetic energy resolution is about 5%.

T_μ

u_z^μ



CCQE

CCπ+

No significant improvement for the muon angle.
Muon angle resolution is better than 1°.

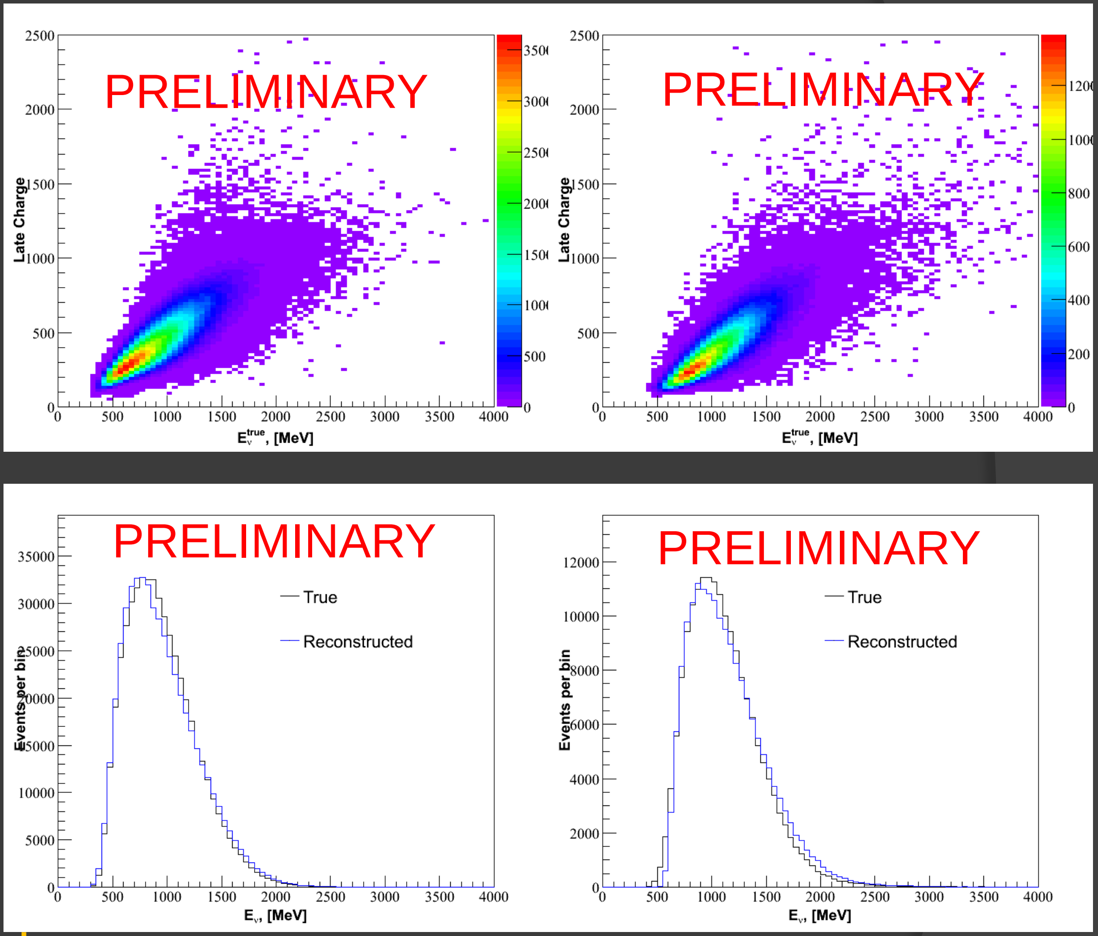
Plots are from MC.

Neutrino Energy Reconstruction Performance

Neutrino energy reconstruction is obtained from the late light charge which is linearly correlated with the true neutrino energy.

The parameters of the reconstruction come from a linear fit to both CCQE and $CC\pi^+$ enhanced samples. the slope parameter is the same in both cases while the Intercept is different.

Energy reconstruction resolution is about 18%.



CCQE CCπ+

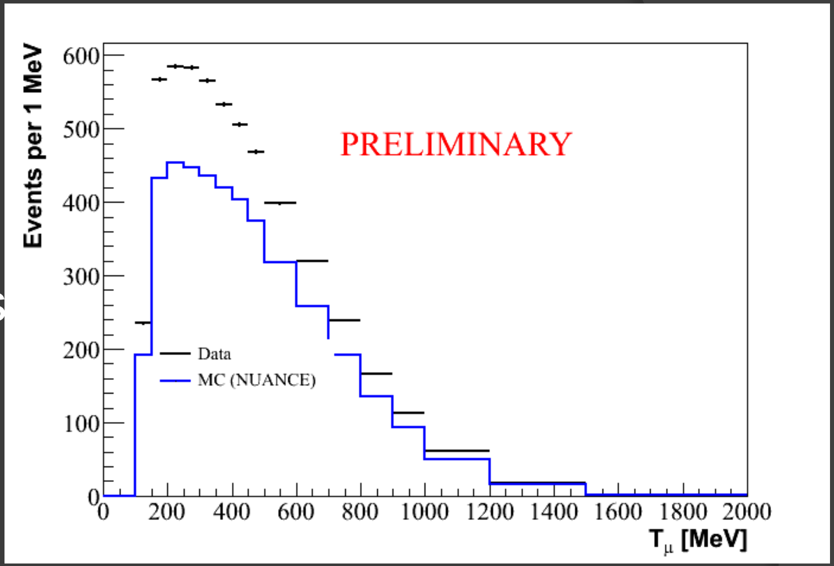
Plots are from MC.

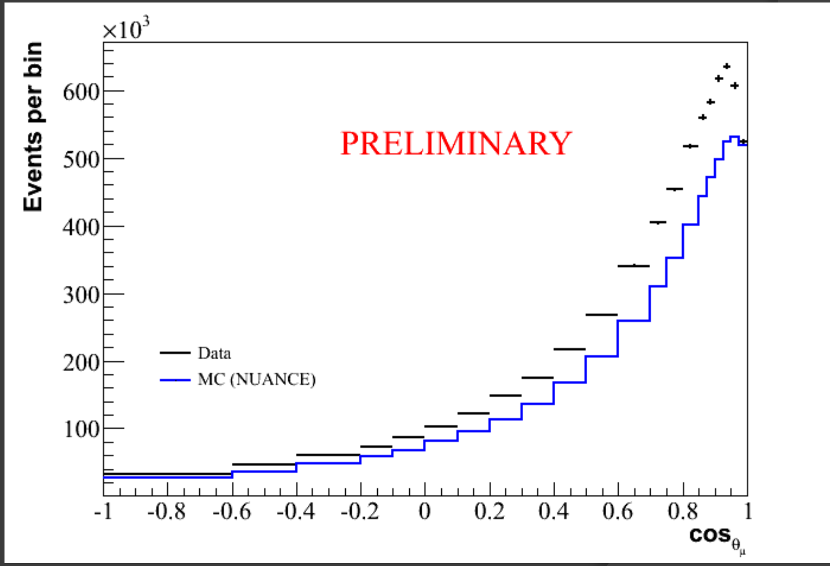
Neutrino Energy– Data Calibration

- So far pure MC – detector response was never tuned for this regime.
- Compare CC Inclusive reconstruction to CCQE and CCπ^+ reconstructions (need to have the same underlying distribution) – reweight MC to the measured CCπ^+ cross section.
- Event-by-event comparison between CC Inclusive and the other reconstructions
- Compare the differences between the reconstructions in data and MC – a way to calibrate.

MiniBooNE CC Inclusive Cross Sections

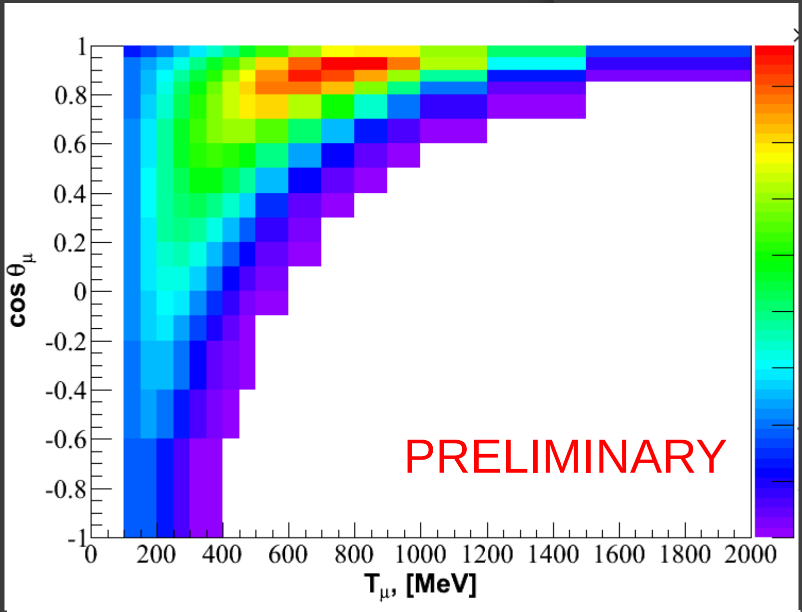
- Data rate is higher than predicted as suggested by the exclusive channels
- Largest neutrino sample in this region to date - 344000 CC inclusive interactions after cuts.
- 4π detector geometry – full coverage of phase space.

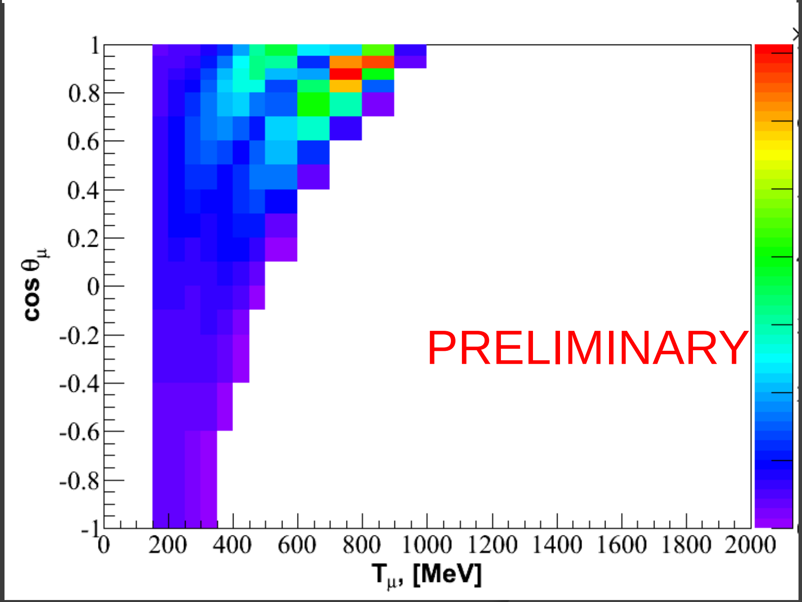




MiniBooNE CC Inclusive Cross Sections

- Complete suite of CC inclusive cross sections.
- Full reconstruction of the lepton vertex without any assumptions for the target!!!
- No dependence on FSI.
- MB will measure $\sigma(E_\nu)$, $d\sigma/dT_\mu(E_\nu)$, $d\sigma/d\cos\theta_\mu(E_\nu)$, $d\sigma/dQ^2(E_\nu)$, flux integrated $d^2\sigma/dT_\mu d\cos\theta_\mu$, $d^2\sigma/dT_\mu d\cos\theta_\mu(E_\nu)$.

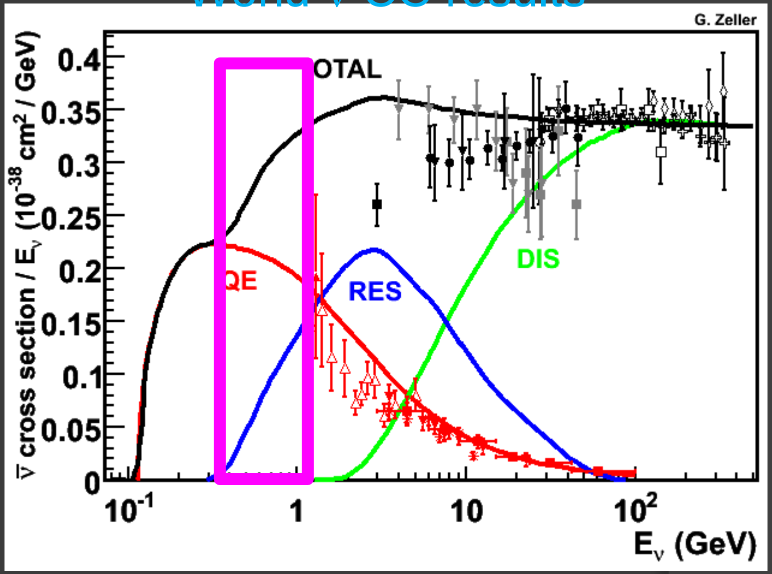




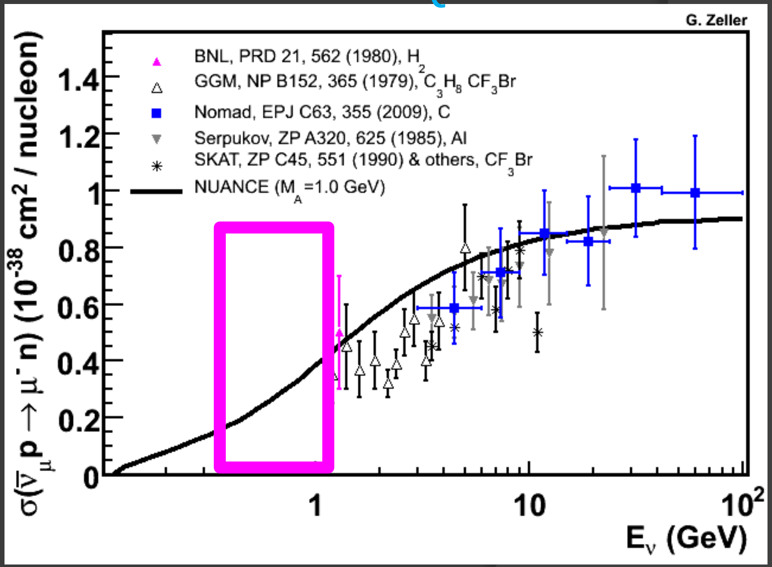
MiniBooNE $\bar{\nu}$ Cross Section Measurements

- Lack of measurements below 1GeV.
- Latest data from NOMAD but in a higher energy region.

World $\bar{\nu}$ CC results



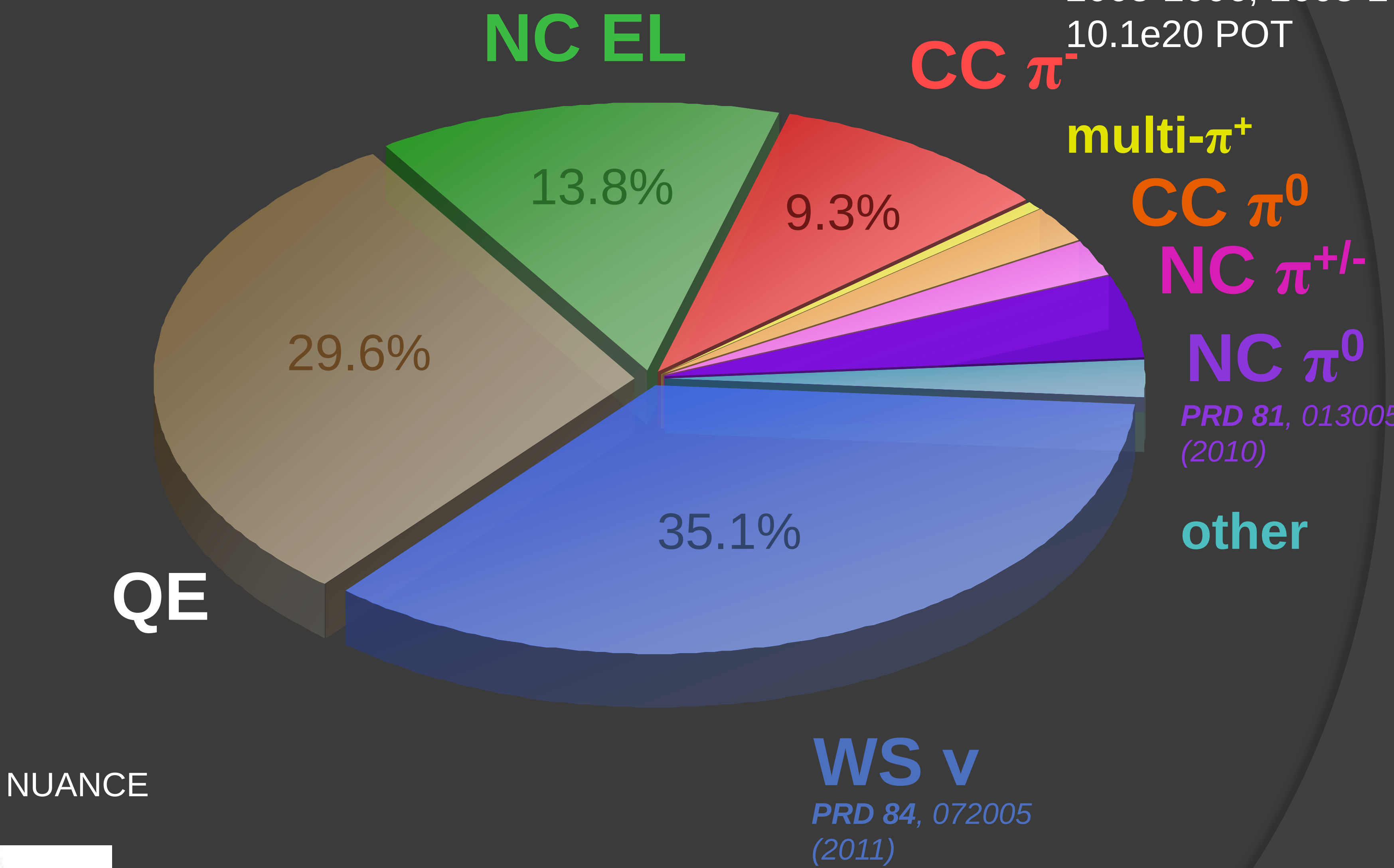
World $\bar{\nu}$ CCQE results



J. Formaggio and G. Zeller, RMP, to be published (2012)

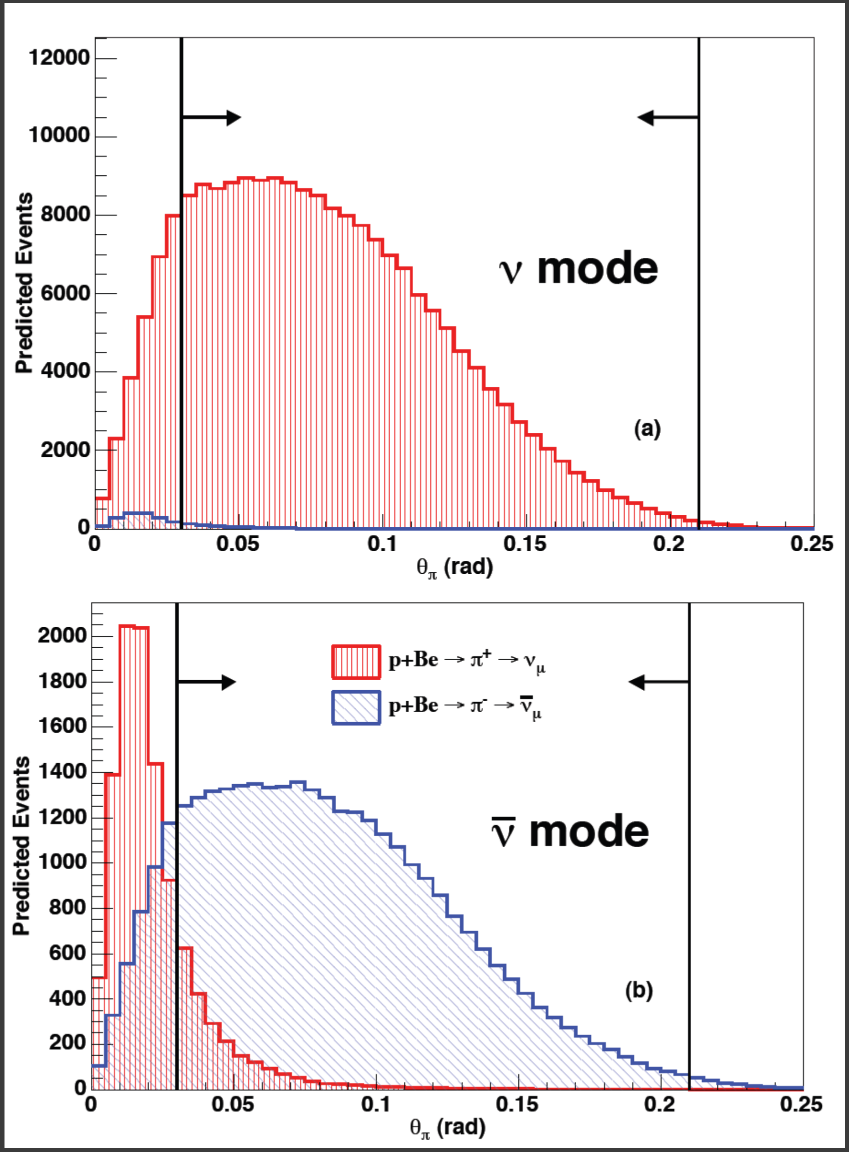
MiniBooNE $\bar{\nu}$ Cross Section Measurements

Collected $\bar{\nu}$ data
2005-2006, 2008-2012
10.1e20 POT



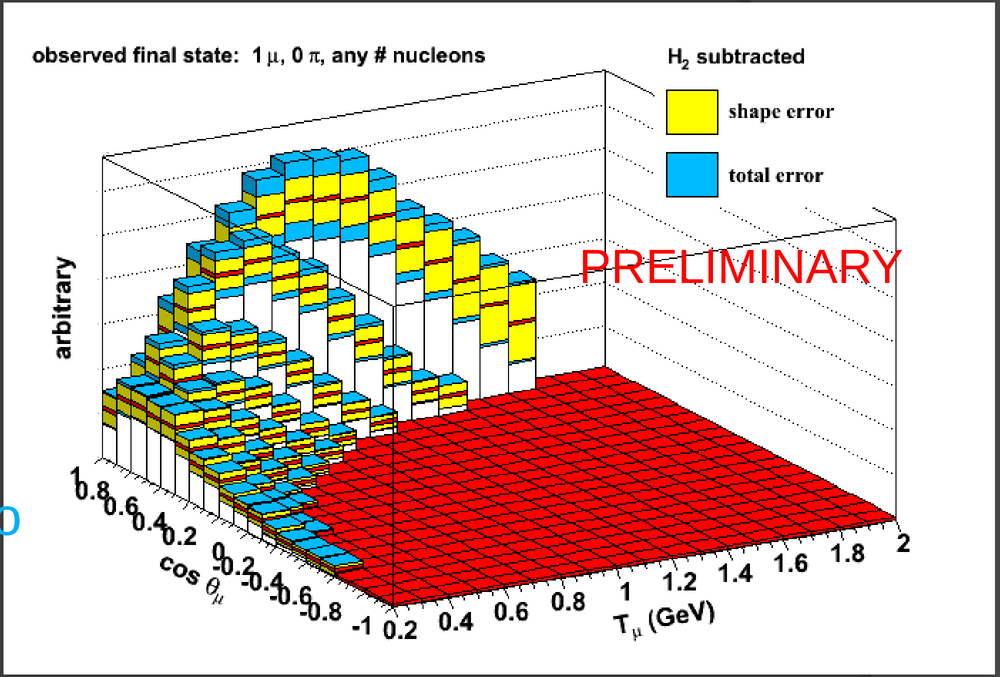
MiniBooNE Wrong Sign ν Component

- Large neutrino component in anti-neutrino mode due to forward pion scattering.
- Not covered by HARP data.
- Constrained by data!!! A first in a non-magnetized detector!!!



Phys. Rev. D84, 072005 (2011)

MiniBooNE $\bar{\nu}$ CCQE Cross Section

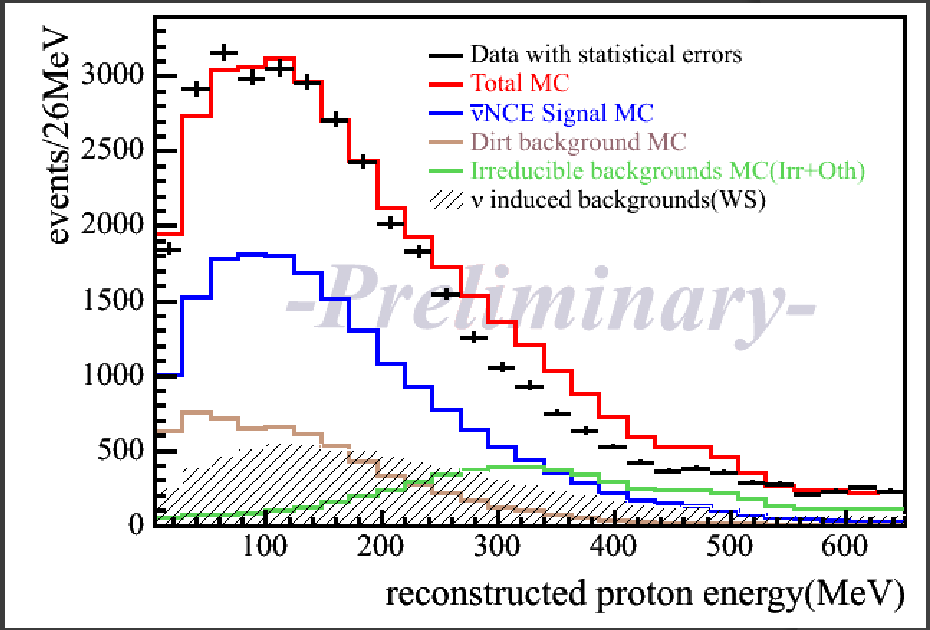


J. Grange, University of Florida

- Full 10.1e20 POT
- Repeat the analysis for anti-neutrino mode with the same cuts.
- 77,000 anti-neutrino events after CCQE cuts.
- Next step is to measure the $\nu/\bar{\nu}$ ratio to cancel systematic errors and constrain the models better.

MiniBooNE $\bar{\nu}$ NC Elastic Cross Section

- Final state – only 1 nucleon mostly below Cherenkov threshold.
- Using scintillation light for reconstruction - calorimeter.
- Using likelihood ratio to separate protons from electrons.
- 7.4e20 POT
- ~44,000 NCE events, 40% purity
- Next step is to measure the $\nu/\bar{\nu}$ ratio to cancel systematic errors and constrain the models better.



R. Dharmaplalan, University of Alabama

Future MiniBooNE Cross Sections Results

New cross section results are coming soon!!!

- Neutrino CC inclusive,
- Anti-neutrino CCQE (Joe Grange, U Florida),
- Anti-neutrino NC elastic (Ranjan Dharmapalan, U Alabama),
- Neutrino CCQE with proton reconstruction (Athula Wickremasinghe, U Cincinnati).

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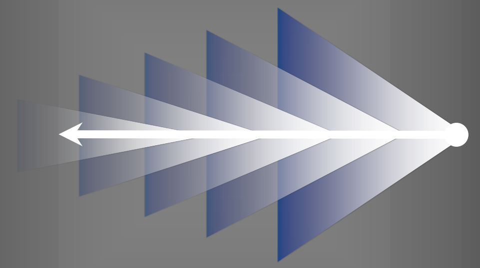
Čerenkov radiation

- Speed of light in mineral oil is 20 cm/ns.
- Threshold is KE > 0.3 mass.
- The angle of the cone is related to the velocity.
- As the particle slows down, the angle gets narrower and the intensity reduces.



$$\cos\theta = \frac{1}{n\beta}$$

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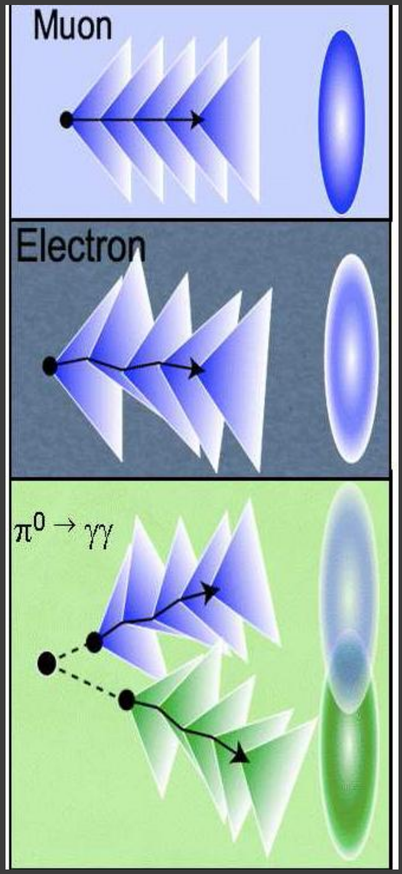
Track Topologies in MiniBooNE Detector

In order to extract a cross section we need to reconstruct the final state particles.



Muon event
- long track, small scattering

Electron/photon event – fuzzy ring
- short track, large scattering
- γ converts and looks like electrons

π^0 event – two fuzzy rings

4π geometry – excellent π^0 detector